Winds of Change

by
Jocelyn Monroe
and
James Battat

in the Hunt for Dark Matter

Physicists love controversy, and the hunt for dark matter has plenty of it. Dark matter is the name for unknown particles which make up approximately 25% of the universe. Recent experimental results in the quarter-century long search for dark matter offer tantalizing hints of a discovery, but flatly contradict one another. The excitement has spurred new thinking in the theoretical interpretation of dark matter search data, and the controversy lends strong support to a new experimental approach under development by the dark matter group in the MIT Department of Physics Laboratory for Nuclear Science (LNS): searching for the dark matter wind.

ASTROPHYSICAL OBSERVATIONS ACCUMULATED SINCE THE 1930s provide overwhelming evidence that dark matter exists and is, in fact, a new particle, fundamentally different from protons, neutrons, electrons and all other Standard Model particles (see "Evidence for Dark Matter," p. 41).[1] Physicists therefore face a question of fundamental importance: What is the dark matter particle?

Although we do not yet know the answer to this question, there are many compelling theoretical candidates. The leading contenders are WIMPs (weakly interacting massive particles) and AXIONS (strongly interacting bantam-weight particles). WIMPs and axions are particles that have arisen naturally in the process of researching other problems in particle physics. An appealing aspect of WIMPs is that their predicted properties, together with cosmologists' picture of the evolution of the universe, result in just the right abundance of WIMPs today to explain dark matter's measured 25% contribution to the composition of the universe.[2] In this article, we focus on searches for WIMP dark matter.

So where are the WIMPs? Direct vs. Indirect Detection

The dark matter distribution in our galaxy is a topic of considerable debate, largely because of the dearth of observational evidence. Under some standard assumptions, the WIMPs form a smooth halo, roughly spherical in shape, that encompasses and extends far beyond the familiar spiral-armed disk of stars and gas (*Figure 1*).[3] The Sun and Earth move through the dark matter halo as they orbit the center of the galaxy once every 240 hundred million years. This motion produces an apparent headwind of WIMP dark matter blowing through Earth-bound laboratories; in the time it takes you to read this sentence, billions of WIMPs have streamed through your body. Of course, the dark matter distribution in the Milky Way halo may be more complicated than the simple spherical model presented above.

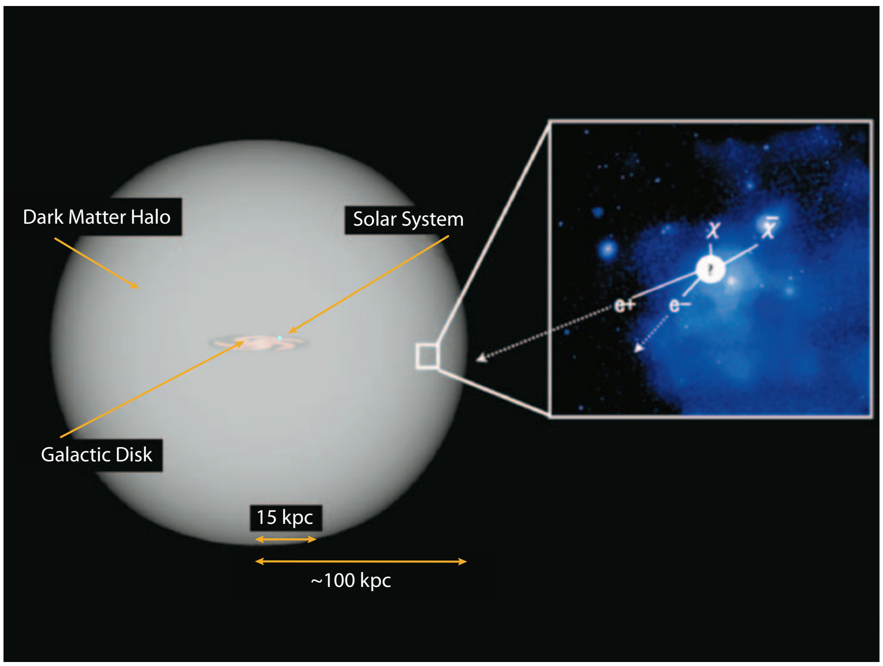

FIGURE 1

Structure of the Milky Way *A schematic description of the standard model for the Milky Way galaxy. The familiar spiral arm structure is embedded in a much larger spherical halo of dark matter. Direct detection experiments look for dark matter streaming through detectors on the Earth. Indirect detection experiments search for the end products of dark matter annihilations with dark anti-matter (e.g., electrons and positrons).*

The hunt is on as physicists around the world attempt to observe dark matter particles interact with individual atoms in the laboratory, or with each other inside our galaxy. Direct detection experiments look for the signal of a dark matter particle entering a terrestrial detector, transferring kinetic energy to a detector nucleus in an elastic scattering interaction, and flying off again. The detector must then sense the recoiling nucleus. Indirect detection experiments search for signatures of dark matter annihilation, which is when a dark matter particle and anti-particle pair collide, destroy each other, and leave behind electron-positron pairs. Indirect experiments seek to detect these final state particles.

Both direct and indirect dark matter detection efforts have their challenges. Direct detection experiments seek to observe a single recoiling nucleus with kinetic energy 0.00001 times the energy released in a single ^{235}U nuclear fission. Many other background processes, due to ambient photon and neutron interactions in a detector, can fake this tiny signal. Indirect detection experiments look for an excess of electrons and/or positrons above the cosmic ray background, which requires a detailed understanding of the local astrophysical sources of cosmic rays. Recent experimental results from Milagro[4] and the Fermi Large Area Telescope (Fermi-LAT),[5] show that there are surprises in the spatial distribution and in the energy spectrum of cosmic ray sources in our galaxy. Neither method has produced a positive dark matter detection verified by multiple experiments, but in the past year proponents of both direct and indirect experiments have observed anomalies which can be explained either as poorly understood backgrounds or as the long-sought signals of dark matter.

Results in 2008 from two indirect dark matter detection experiments, PAMELA[6] and ATIC,[7] have generated great excitement, with measurements that could be consistent with a dark matter annihilation signal. However, results in 2009 from Fermi-LAT flatly contradict ATIC, with no evidence for dark matter in a comparable search. As of May 2009, the jury is still out on whether the mysterious excesses in the data from PAMELA and ATIC are caused by dark matter annihilation or faked by an unaccounted for local astrophysical source. Direct WIMP detection experiments have all reported no evidence for dark matter scattering,[8] with just one exception. In 2008, the DAMA/Libra[9] collaboration reported a modulation signal in its detector, which is strikingly consistent with the expectation for dark matter given the motion of the Earth around the Sun, through the dark matter halo. This result is hotly debated because it appears inconsistent with a number of other direct detection experiments. Thus the question is: Does the DAMA/Libra collaboration really understand its sources of background?

Searching for the Dark Matter Wind

The controversy motivates new ways for searching for dark matter that are less susceptible to background fakes. The dark matter group at LNS (Professors Fisher, Monroe, Sciolla, and Yamamoto; Pappalardo Fellow Dr. James Battat and Dr. Denis Dujmic; and graduate students Shawn Henderson, Asher Kaboth, and Jeremy Lopez), are pursuing a new idea to blow away the background problem—searching for the dark matter wind.

As the Sun moves through the WIMP halo, we expect to experience a headwind of WIMPs blowing opposite to our direction of motion through the Galaxy (*Figure 2*). By chance alignment, our Galactic orbital vector points toward the constellation Cygnus, so the WIMP wind should appear to blow from Cygnus.

Evidence for Dark Matter

The first observational evidence for dark matter came in 1937, when astronomer Fritz Zwicky observed the Coma cluster, a collection of over 1,000 galaxies that are gravitationally bound together. To his surprise, Zwicky found that the individual galaxies in the cluster were moving at speeds far too fast to be explained by the mass visible to his telescope alone.[12] Zwicky's work lay largely unreferenced for nearly 40 years until Vera Rubin, an astronomer at the Carnegie Institution for Science in Washington, D.C., found that the orbital velocities of stars in spiral galaxies were larger than could be explained by the visible matter in the galaxy.[13] Together, Zwicky's and Rubin's observations made it clear that there was matter in the universe that eluded detection with the telescopes and detectors of their day.

Advances in technology have revealed that some of Zwicky's and Rubin's missing mass is simply "regular" matter that was either too dim to see or that emitted primarily at unexplored wavelengths. For example, X-ray telescope observations show that galaxy clusters contain a significant amount of million-degree gas that was undetectable in Zwicky's day (until 1962, no cosmic X-ray sources were known). However, from precision observations of the Cosmic Microwave Background and measurements of the cosmic abundances of light elements, we now know that dark matter primarily consists of a new particle.[14] Dark matter is fundamentally different from all particles in the Standard Model of particle physics.

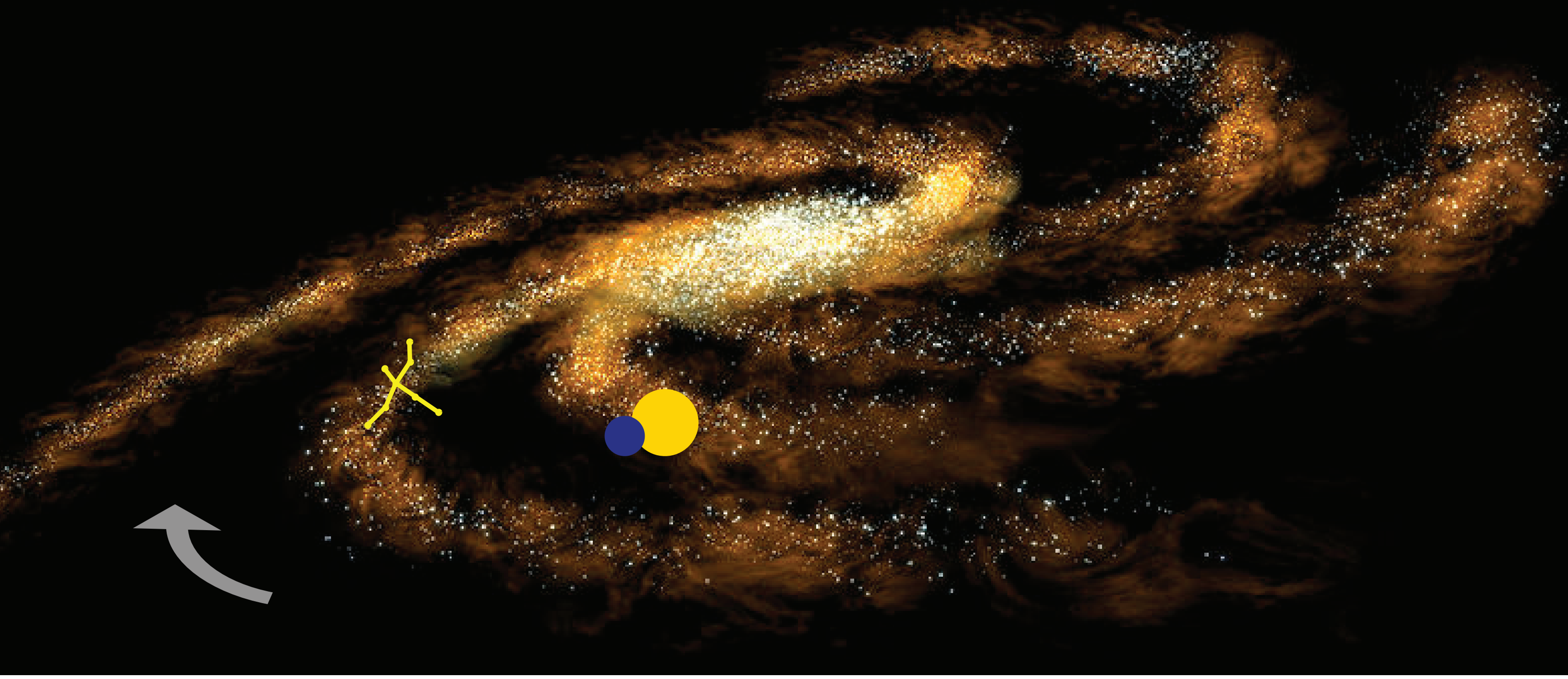

FIGURE 2

Milky Way Earth-Sun Motion *In this artist's rendition of the Milky Way galaxy, we see the familiar spiral arms. The Sun and Earth, shown here schematically as yellow and blue circles, move along a nearly circular orbit about the center of the galaxy. Coincidentally, this motion points toward the constellation Cygnus, the Swan, shown here in yellow. (Based on image courtesy of NASA)*

As the Earth revolves about its axis each day, the position of Cygnus will sweep out a circle on the celestial sphere. From the perspective of a detector at MIT, the WIMP wind will appear to blow at one time from the horizon, and then twelve hours later from directly overhead (*Figure 3*).[10] No known background source exhibits this angular modulation. Therefore measurements of the arrival direction of recoil-inducing particles can unambiguously separate the sought-after WIMPs from insidious backgrounds.

The incoming direction of a WIMP can be determined by measuring the angle and direction of the struck nucleus as it recoils, just as if the WIMP were the cue ball in a game of pool. In the solid or liquid targets of the leading dark matter detectors (CDMS and Xenon10), recoiling nuclei travel only nanometers or less; in a diffuse gas target, however, WIMP-induced nuclear recoils will extend several millimeters—long enough to accurately measure the recoil track direction. The headwind of WIMPs will produce a characteristic angular distribution of nuclear

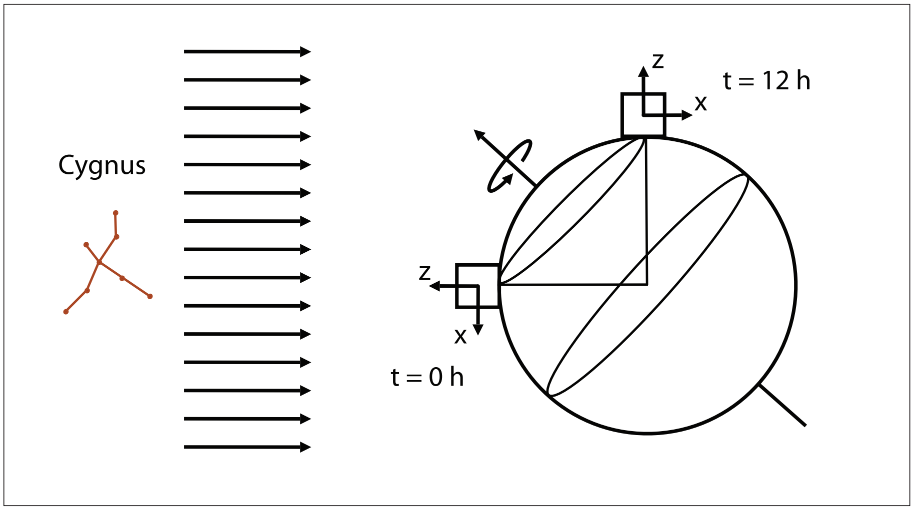

FIGURE 3

Daily Modulation *As the Earth moves through the galactic halo, we experience a head-wind of WIMP dark matter particles that appears to come from the Cygnus constellation. For a detector located at MIT (latitude ~42˚), the direction of the WIMP wind will change over the course of the day as the Earth rotates. Here, we show an MIT lab at two time periods. Initially, the WIMPs appear to come from overhead; twelve hours later, the wind has shifted to the horizon.*

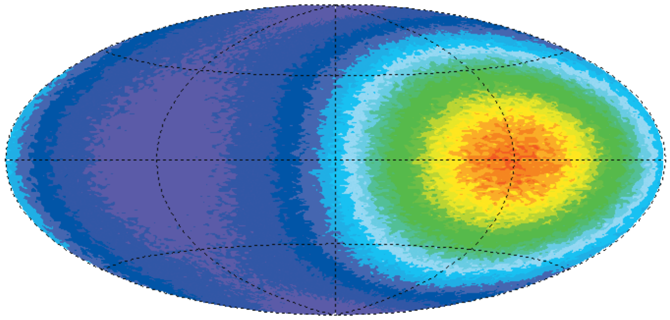

FIGURE 4

Skymap *In a directional dark matter detector, the recoiling gas nucleus encodes information about the initial direction of the WIMP. This figure shows a map of the sky, in galactic coordinates. The color contours show a simulation of the distribution of nuclear recoil angles expected in our detector under standard assumptions for the galactic dark matter distribution. The recoil directions are concentrated 180˚ away from Cygnus. A directional dark matter detector looks for this anisotropy.*

recoil angles. *Figure 4* shows the expected angular distribution for a typical WIMP halo model. By constructing a sky map of the observed nuclear recoil angles, a dark matter detector can look for this strong angular anisotropy.

The Dark Matter Time Projection Chamber

The Dark Matter Time Projection Chamber (DMTPC) collaboration has successfully developed a dark matter detector that is sensitive to the direction of arrival of dark matter particles. The detector (shown schematically in *Figure 5*) consists of CF_4 gas at ~10% of atmospheric pressure. As a WIMP-struck nucleus recoils, it ionizes nearby gas molecules. The liberated electrons drift in an electric field toward an amplification region, which boosts the charge signal and produces scintillation light. Using a CCD camera, our detector literally takes a photograph of the recoiling nucleus track projected onto the amplification plane. *Figure 6* shows a typical image of a neutron-induced nuclear recoil.[11]

Background events from photons and radon-related radioactivity are easily separated from nuclear recoils by comparing the track length and net photon intensity (*Figure 7*). In addition, since nuclear recoils produce more scintillation light at the start of the recoil than at the end as their energy loss varies with energy, the light profile along a track reveals the vector direction of the recoil.

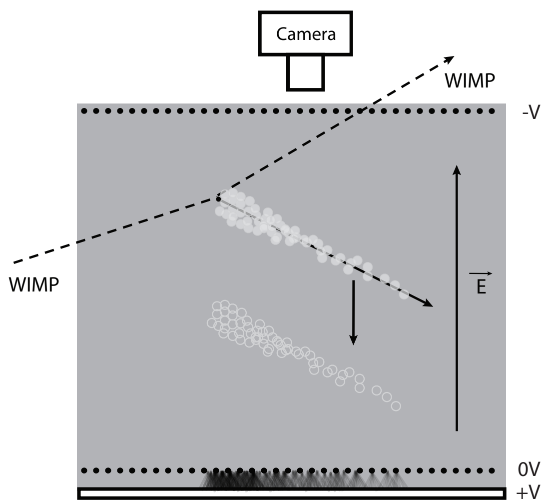

FIGURE 5

Detector Schematic *A schematic side-view of the cylindrical DMTPC detector. The dotted lines are metal meshes that establish a drift electric field. The low-pressure (0.1 atmosphere) CF_4 gas is represented by the light grey rectangle. A gas nucleus (black circle) struck by a WIMP (dashed line) will recoil and ionize the surrounding gas. The ionized electrons, shown as a cluster of grey circles, drift under the electric field toward the bottom amplification region where scintillation light is produced. This light track is imaged by a CCD camera. A sample track image is shown in Fig. 6.*

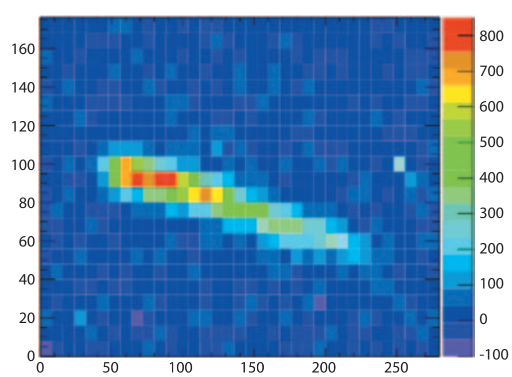

FIGURE 6

Neutron Recoil Image *An image of the scintillation light generated by a fluorine nucleus recoiling in the detector. The recoil was generated by a neutron incident from the left. The recoil track is clearly discernable.*

Four years ago, this detector was just a concept on paper; now, the DMTPC collaboration has built it and demonstrated its ability to reconstruct the dark matter wind direction. Thus far, the detector development has taken place at MIT, in the basement of building NW13. This summer, we will take the detector underground to the Waste Isolation Pilot Plant (WIPP) facility in New Mexico, where it will be shielded from cosmic rays, and thus suppress the rate of fake events from neutron-induced recoils. At WIPP, nearly half-a-mile below the Earth's surface, we will use this diffuse-gas TPC technology to begin our search for the WIMP wind.

Despite the astronomical (in both senses of the word) evidence for dark matter, no confirmed direct or indirect detection of dark matter particles has yet been made. Copious backgrounds that can swamp sensitive detectors are the main obstacles to successfully detecting dark matter particles. By measuring the direction of nuclear recoils, DMTPC is poised to provide a new kind information about dark matter, at a time when the field might just be on the brink of a major discovery. The answer to the dark matter puzzle may be blowing in the wind.

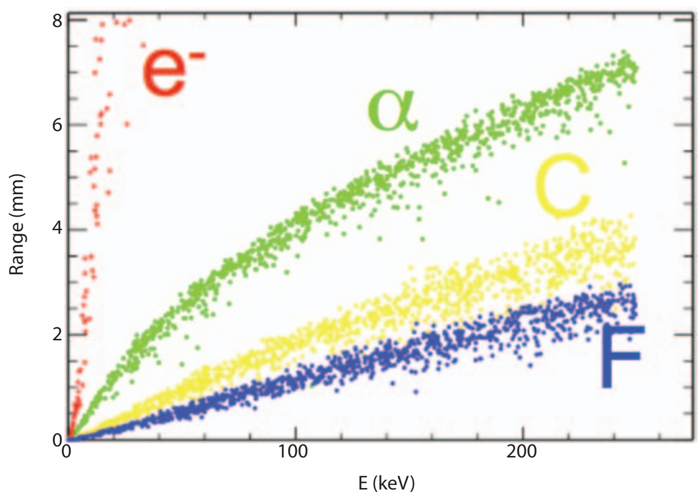

FIGURE 7

Range vs. Energy *The track length and total energy can be used to identify the particle. Here, we show a simulation of the track length (range) vs. recoiling energy for electrons, alpha particles, carbon nuclei, and fluorine nuclei moving through CF_4 gas at 0.1 atmosphere. Nuclear recoils (C, F), can be efficiently distinguished from electron and alpha particle backgrounds.*

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JOCELYN MONROE *is an Assistant Professor in the MIT Department of Physics. From 2006-2009 Jocelyn was a Pappalardo Fellow in MIT's Laboratory for Nuclear Science. Jocelyn earned her Ph.D. from Columbia University in 2006. In 1999-2000, she held the position of Engineering Physicist at the Fermi National Accelerator Laboratory. Jocelyn earned her B.A. in Astrophysics at Columbia University in 1999.*

JAMES BATTAT *is a Pappalardo Fellow in Physics at MIT. His research interests include searches for dark matter and observational tests of gravity. His Ph.D. research at Harvard employed precision lunar and planetary ranging to probe gravity in the Solar System. At MIT, he works on the DMTPC dark matter direct detection experiment. James received his Sc.B. in Physics from Brown University in 2001.*